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NASA TM X-65327

P. J. HEFFERNAN

OCTOBER 1970

FACILITY FORM 602

N70-393 0 9
(ACCESSION NUMBER)

26
(PAGES)

TMX 65327
(NASA CR OR TMX OR AD NUMBER)

1
(THRU)

07
(CODE)

07
(CATEGORY)



GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

X-751-70-308
Preprint *

TELECOMMUNICATIONS CAPABILITIES
OF THE GSFC MARK I
TRACKING AND DATA RELAY SATELLITE

P. J. HEFFERNAN

OCTOBER 1970

*This is a preprint of a paper prepared for the 1970 International
Telemetry Conference.

Telecommunications Capabilities of the GSFC Mark 1 Tracking and Data Relay Satellite

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Summary. - A spacecraft concept for the NASA Tracking and Data Relay Satellite (TDRS) mission is described. The proposed design, based on the use of current space-proven technology and compatible with existing launch vehicle constraints, provides telecommunications support to earth-orbiting spacecraft at VHF, S-, X- and K-Band frequencies. A summary is given of key Mark 1 RF parameters including transmit effective radiated power (ERP) and receiving system gain-to-temperature ratio (G/T) at the several frequencies of operation. On the basis of the RF parameters postulated, data are presented on system signaling rates and performance thresholds with user spacecraft ERP and G/T as parameters. The results, presented as a family of parametric nomographs, provide a concise summary of the telecommunications capabilities of the GSFC Mark 1 TDRS spacecraft design.

Introduction. - The idea of using tracking and data relay satellites (TDRS) to supplement and/or replace ground stations in supporting low-altitude earth-orbiting spacecraft has been of interest to the telemetering community since the concept was first advanced in the early 1960's. In particular, both NASA and the Air Force have sponsored studies¹⁻⁶ aimed at developing information regarding the technical characteristics, operational features, and general feasibility of TDRS systems. These studies have shown that a properly instrumented network of synchronous relay satellites can provide complete command, tracking, and data acquisition coverage for a wide range of programs including manned and automated space research and applications missions. Potentially, a TDRS system could not only reduce the number of ground stations required for effective support of near-earth missions but could also lead to significantly increased capabilities in the areas of communications and orbit determination/update.

Assured that major elements of the communications satellite technology postulated in early TDRS studies had been developed and proven in the course of the ATS, INTELSAT, and TACSATCOM programs, NASA's Office of Space Sciences and Applications directed the Goddard Space Flight Center* (GSFC) to conduct a formal Phase A study of spacecraft and system concepts applicable to a TDRS flight program in the early to mid 1970's time frame. This study, performed during fiscal years 1969 and 1970, resulted in the detailed conceptual design of a TDRS spacecraft based entirely on state-of-the-art dual-spin technology and compatible with NASA's available family of launch vehicles. The baseline GSFC TDRS spacecraft concept, designated the Mark 1A, provides limited support to cooperating user spacecraft and VHF and S-Band. Alternate TDRS spacecraft configurations derived from the baseline design and designated the Mark 1B, Mark 1C, and Mark 1C (augmented) provide increased telecommunications support (including wide-

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A concurrent Phase A TDRS study was performed at the Jet Propulsion Laboratory⁸. This study concentrated on concepts for advanced TDRS spacecraft available for launch in the mid to late 1970's time frame.

band links at X- and K-Bands) but are more complex and require correspondingly greater launch vehicle capability.

This paper describes the proposed Mark 1 series of TDRS spacecraft with emphasis on telecommunications and antenna subsystems. A key RF parameter of effective radiated power (ERP) or receiving system gain-to-temperature ratio (G/T) is identified for each of the TDRS operating frequencies. The telecommunications capacities of the various TDRS/user and user/TDRS RF links are presented in a normalized form based on standardized user RF parameters. On the basis of estimated channel capacity requirements for specific TDRS support services, actual user RF requirements are presented in the form of nomographs indicating the trade-offs available in user antenna directivity, transmit power, and/or receiver noise figure. These nomographs provide a useful summary of the telecommunications capabilities of the GSFC Mark 1 TDRS spacecraft by showing explicit relationships between user RF complexity and system signalling rates and performance thresholds.

Mark 1 Spacecraft Description. - The baseline Mark 1A TDRS spacecraft is illustrated in Figure 1. The configuration is similar to both TACSATCOM⁹ and INTELSAT IV¹⁰, i.e. a spin-stabilized outer shell with a large scale internal despun section providing a projecting earth-orientated platform on which the prime telecommunications antennas are located. State-of-the-art sensors are used for attitude determination and despun phasing, and a monopropellant hydrazine subsystem provides for orientation maneuvers, station seeking, and east-west station keeping, injection errors and spin control. A phase-lock control operation of the despun platform provides east-west pointing, slewing, and tracking functions.

The despun section contains a rigid 8-foot diameter S-Band parabolic antenna and a VHF antenna consisting of an array of four cross-polarized foldable yagi elements. These antennas are used in RF links to and from cooperating user spacecraft. In addition, the despun section contains a set of three X-Band horn antennas used in RF links between TDRS and ground.

The spinning section of the Mark 1 spacecraft contains the entire solar array, the power and attitude control subsystems, and the apogee motor. A redundant housekeeping telemetry and command subsystem is housed in the spinning section for mission support during the launch phase and as a backup for the prime telemetry and command subsystem housed in the despun section together with the multi-frequency telecommunications repeater.

An estimated overall spacecraft weight of 805 lbs. includes that of a spent JPL scaled Starfinder apogee motor and is compatible with launch by an SLV-3A/Centaur combination vehicle.

The 8-foot reflector has a line array of circularly polarized S-Band feeds which can be switched to provide north-south pointing of a nominal 3° S-Band beam out to ± 13° relative to the sub-satellite point. East-west pointing is provided by slipping the phase of the despun platform to ± 13°, thus providing S-Band beam steering within a 26° cone of coverage required for support of most near-earth spacecraft. The Mark 1A S-Band beam pointing scheme thus provides two-way links to any single user spacecraft; support of more than one user at S-Band implies that the two users are both within the 3° antenna beam.

The four VHF yagi elements constitute a phased array which transmits to user spacecraft using circular polarization and has the capability of receiving vertical and horizontal linear polarizations independently. Phasing net-

works correct for the possible $\pm 13^\circ$ east-west pointing error caused by physical pointing of the stabilized platform in tracking S-Band user spacecraft. The four elements thus produce a single 26° antenna beam which is always centered on the sub-satellite point. This single beam supports multiple VHF users^{9,10}.

Each of the three X-Band horn antennas has a nominal gain of 20 db. They are arranged with over-lapping patterns in the east-west plane. One of the three is used to provide links with the ground, with automatic switching as required when the stabilized platform is pointed away from the sub-satellite point during S-Band beam steering.

The telecommunications subsystem of the Mark 1A may be described as a two-way coherent multiple-channel frequency translating repeater. Signals received from the ground at X-Band are repeated to user spacecraft at either VHF or S-Band or both; signals received from VHF and S-Band users are relayed to the ground at X-Band. A working frequency plan for the Mark 1A is given in Figure 3(A). A basic subsystem design exists including the frequency generation and synthesis circuitry and IF processing units. This design is based in part on a communications subsystem design developed for ATS-F&G¹¹.

The Mark 1B, Mark 1C, and Mark 1C (augmented) spacecraft are all elaborations on the basic Mark 1A design. The Mark 1B is an intermediate capability spacecraft providing multiple beams at S-Band; it will not be discussed further. The Mark 1C TDRS, shown in Figure 2, differs from the Mark 1A in the following particulars: the 8-foot dish is fully gimballed and has a rotating linear array of circularly polarized S-Band feeds providing two each transmit/receive beams; the addition of two fully-gimballed 4-foot dishes equipped with X-Band feeds; use of a larger apogee motor; increased solar cell area; and incorporation of additional capability in the repeater subsystem. The Mark 1C can thus accommodate a minimum of two S-Band users and 2 X-Band users, plus multiple users at VHF. A slight variant of the Mark 1C would replace the two S-Band beam capability with selectable S- or X-Band single beam capability. The Mark 1C (augmented) TDRS differs from the basic Mark 1C in that K-Band feeds are incorporated into the 4-foot dishes as well as X-Band feeds. Working frequency plans for the two versions of the Mark 1C are shown in Figures 3(B) and 3(C).

In general, it can be asserted that the baseline channel capacities of the several RF links between the TDRS and ground are so great compared to the channel capacities of links between TDRS and users that the performances of the latter are established exclusively by the RF parameters of the TDRS and users. Thus, the telecommunications capabilities of the Mark 1 can be discussed in terms of the P/KT ratio channel capacity* available in a given TDRS/user vs. that required for the telecommunications support service in question.

Normalized Link Channel Capacities. - A summary of the major RF parameters of the Mark 1 series of TDRS spacecraft is given in Table 1. To relate these parameters to link channel capacities, it is necessary to specify the RF parameters of candidate user spacecraft and perform power budget analy-

*See Appendix.

ses. A complete set of such analyses has been documented elsewhere⁷ and two representative examples are reproduced here to illustrate the approach taken and the methodology used. The two links considered here in detail are a VHF user/TDRS link (of interest, for example, for emergency voice links with manned vehicles) and an X-Band TDRS/user link (of interest for wideband or video links to advanced manned spacecraft).

The selected approach is to compute nominal and worst case ratios of available average received power P to white gaussian thermal noise power spectral density KT in reference TDRS/user or user/TDRS links using normalized user ERP and G/T^* . The normalized P/KT ratios computed in power budget analyses can then be related to the actual P/KT ratios which will be obtained in links to specified users simply by identifying the users' RF parameters relative to the reference values assumed.

Example A: VHF User/TDRS Link. - Basic parameters of the Mark 1 user/TDRS RF link are:

Nominal link frequency	137 MHz
Normalized user ERP	1 watt
Transmit polarization	unspecified
Nominal mutual range	41,000 km
Mark 1 receive G/T	-14 db/°K

Based on these parameters, a detailed link power budget computation is given in Table 2. The calculation indicates that in the worst case anticipated, a normalized P/KT ratio of +41.1 db-Hz will obtain in a VHF user/TDRS link. On the assumption that the link is thermal noise limited, this figure can be related to the signalling rates achievable by a specification of the user's actual ERP relative to 0 dbw. User ERP requirements vs. signalling rates showing typical thresholds of minimum performance are given in Figure 4, based on the P/KT requirements discussion of the Appendix. It is seen that the 0 dbw ERP situation will suffice for a given range and range-rate system but will not suffice for emergency voice transmissions. Alternatively, Figure 4 shows that users with a VHF ERP of 10 watts can achieve PSK digital data transmissions at rates slightly in excess of 10 kilobits.

It is noted in passing that user/TDRS communications may not, in practice, be thermal noise limited. For a discussion of such conditions, see^{9,10}.

Example B: X-Band TDRS/user Link. - The Mark 1C TDRS can be implemented to transmit to user spacecraft at X-Band using either an 8-foot dish or a 4-foot dish. The normalized link analysis given here will consider both cases. The basic link parameters are:

Nominal link frequency	7.9 GHz
Nominal Mark 1C ERP (two cases)	+46 dbw (4'), +52 dbw (8')
Transmit Polarization	Circular

*A normalized ERP is defined here to be 0 dbw; this corresponds to the case of a 1 watt transmitter driving an ideal isotropic antenna. A normalized G/T is defined here to be -30 db/°K; this corresponds to the case of a receiving system with a truly isotropic antenna and an effective overall system noise temperature of 1000°K.

TABLE 1

Summary of TDRS RF Parameters

Proposed TDRS Configuration	Function & Frequency	RF Implementation	RF Performance Parameter
Version C, K-band augmented	VHF transmit, f_c nominal = 149 MHz	VHF array antenna, 20 watts RF power	ERP $\geq +26$ dbw, circular polarization
	VHF receive, f_c nominal = 137 MHz	VHF array antenna, 1000 °K system temp.	G/T ≥ -14 db/°K, polarization diversity
	S-band transmit, f_c nominal = 1800 MHz	8' dish, scanned, 20 watts RF power	ERP $\geq +39$ dbw, circular polarization
	S-band receive, f_c nominal = 2250 MHz	8' dish, scanned, 1000 °K system temp.	G/T $\geq +6$ db/°K, circular polarization
	X-band transmit, f_c nominal = 7.9 MHz	4' dish, gimbaled, 10 watts RF power	ERP $\geq +46$ dbw, circular polarization
	X-band receive, f_c nominal = 8.4 MHz	4' dish, gimbaled, 1000 °K system temp.	G/T $\geq +5$ db/°K, circular polarization
	X-band transmit, f_c nominal = 7.9 MHz	8' dish, gimbaled, 10 watts RF power	ERP $\geq +52$ dbw, circular polarization
	X-band receive, f_c nominal = 8.4 MHz	8' dish, gimbaled, 1000 °K system temp.	G/T $\geq +11$ db/°K, circular polarization
	K-band transmit, f_c nominal = 14.3 GHz	4' dish, gimbaled, 10 watts RF power	ERP $\geq +52$ dbw, circular polarization
	K-band receive, f_c nominal = 15.3 GHz	4' dish, gimbaled, 1000 °K system temp.	G/T $\geq +12$ db/°K, circular polarization
	Version C, alternate		
	Version C		
	Version A		

TABLE 2

User/TDRS VHF-Link Analysis

Parameter	Nominal Value	Worst-Case Tolerance (db)
Normalized user ERP	0.0 dbw	-
Free-space spreading loss	-167.0 db	-0.5
Polarization loss	-0.5 db	-0.5
Antenna pointing losses	-1.0 db	-1.0
Miscellaneous losses	-0.5 db	-0.5
Mk 1 G/T	-14.0 db/°K	-1.0
Boltzmann's constant, K	-228.6 dbw/°K-Hz	-
Normalized link P/KT	+45.6 db-Hz	-3.5
Allowance for signal-to-noise degradation in TDRS/ground link	-1.0 db	-
Normalized overall link P/KT	+44.6 db	-3.5

(TDRS/user X-Band Link Parameters, cont'd)

Nominal mutual range	41,000 km
Normalized user G/T	-30 db/°K

A detailed power budget analysis for the X-Band TDRS/user link is given in Table 3. The calculated worst case P/KT ratio is +40.8 db-Hz for the 8' antenna case and +34.8 db-Hz for the 4' antenna case. The actual P/KT ratio realized in actual operations depends on the user spacecraft's G/T ratio relative to the reference value of -30 db/°K. Working with the 8' TDRS antenna case, typical signaling relationships are shown in Figure 5. It is seen that megabit data up-links to user spacecraft will require a user G/T of at least +6.4 db/°K. Television links will require a minimum G/T of +9.3 db/°K; emergency voice, on the other hand, requires only -28 db/°K, a sensitivity realizable with minimum user spacecraft directivity.

On the basis of the normalized P/KT calculations worked out here and using the results of similar analyses for the remaining RF links⁷, Table 4 contains a summary of the Mark I normalized link channel capacities.

TABLE 3

TDRS/User X-Band-Link Analysis

Parameter	Nominal Value	Worst-Case Tolerance (db)
Mk 1 ERP	+46 dbw (4') +52 dbw (8')	-1.0
Free-space spreading loss	-202.8 db	-0.5
Polarization loss	-0.5 db	-1.0
Antenna pointing losses	-1.0 db	-1.0 db
Miscellaneous losses	-0.5 db	-0.5 db
Normalized user G/T	-30.0 db/°K	-
Boltzmann's constant, K	-228.6 dbw/°K-Hz	-
Normalized link P/KT	+39.8 db-Hz (4') +45.8 db-Hz (8')	-4.0
Allowance for signal-to-noise degradation in TDRS/ground link	-1.0 db	-
Normalized overall link P/KT	+38.8 db-Hz (4') +44.8 db-Hz (8')	-4.0

User RF Implementation vs. Signaling Rate. - Using the summary of normalized Mark 1 link channel capacities given in Table 4, system signaling rates and thresholds of minimum performance are related to actual user RF implementations in Figures 6 through 13. In the case of TDRS/user links, these nomographs relate signaling rates to user G/T and also to actual user hardware implementation - i.e., noise figures and antenna diameters. In the case of user/TDRS links, the nomographs relate signaling rates to user ERP and also to the hardware implementation - i.e., transmit power and antenna diameter. A particularly attractive feature of this method of presentation is that the trade-offs in antenna size and RF component rating are displayed very clearly.

Figures 6 through 13 provide a comprehensive parametric summary of the telecommunications capabilities of the GSFC Mark 1 TDRS in its several postulated configurations. Inspection of the indicated trade-offs in realization of required ERP and G/T parameters indicates that the Mark 1 TDRS can

TABLE 4

Summary of Normalized RF-Link Parameters

Proposed TDRS Configuration	RF Link	Normalized P/KT (db-Hz)	
		Nominal	Worst-Case
Version C, K-band augmented	VHF, TDRS/user	54.6	49.1
	VHF, user/TDRS	44.6	41.1
	S-band, TDRS/user	44.9	40.9
	S-band, user/TDRS	33.8	29.8
	X-band, TDRS/user (using 4-ft dish)	38.8	34.8
	X-band, user/TDRS (using 4-ft dish)	27.5	23.5
	X-band, TDRS/user (using 8-ft dish)	44.8	40.8
	X-band, user/TDRS (using 8-ft dish)	33.5	29.5
	K-band, TDRS/user	38.7	33.2
	K-band, user/TDRS	28.4	22.9
Version C, alternate			
Version C			
Version A			

provide significant telecommunications support to low-altitude earth-orbiting user spacecraft without imposing undue burdens in terms of required user spacecraft RF complexity.

Acknowledgement. - The TDRS telecommunications analysis presented in this paper was developed in the course of a TDRS system study performed at GSFC under the direction of R.A. Stampfl. The author is indebted to the members of the GSFC study team for their contributions to the spacecraft and system concepts described. In particular, he wishes to express his gratitude to R.A. Stampfl, E.J. Habib, and F.S. Flatow for their comments, suggestions, and constant encouragement.

APPENDIX

CHANNEL CAPACITY REQUIREMENTS FOR TDRS SUPPORT SERVICES

Introduction. - This appendix is a highly condensed summary of a detailed study documented in the GSFC Final Study Report on TDRS^{*}. The purpose of this appendix is to indicate the bases for the several P/KT channel capacity^{*} requirement estimates used in deriving Figures 4 through 13. Available space does not permit extensive discussion. Further details are available in the GSFC study report⁷.

Digital Data Transmission. - For TDRS/user links, assume incoherent binary FSK. Allow a 4 db margin above the energy contrast ratio required for a bit error probability of 10^{-5} . Thus, P/KT for this service is given by $17.3 + 10\log_{10}R$, db-Hz, where R is the signaling rate in bits per second. For user/TDRS links, assume coherent binary PSK. The energy contrast ratio required for a bit error probability of 10^{-5} is +9.4 db. Thus, the P/KT requirement for a transmission rate R is $9.4 + 10\log_{10}R$, db-Hz.

Emergency Voice. - Assume analog transmission of clipped speech using narrowband FM with feedback detection. Minimum acceptable intelligibility for this implementation corresponds to a P/KT of the order of +43.0 db-Hz. This is the value used in Figures 4 through 13.

Video. - Assume standard EIA RS-170 format but band-limit prior to trans-

* Throughout this paper, ratios of average available signal power P to available white gaussian noise spectral density KT have been termed channel capacities. This convention arises from a loose interpretation of Shannon's well known theorem for the channel capacity of the band-limited gaussian channel. This theorem states that for a system bandwidth B, received signal power P, and noise density KT the function

$$C(P, KT, B) = B \ln(1 + P/KTB)$$

defines the maximum information rate (in natural units) which can be supported without error. For fixed P/KT, the C function is maximized by letting B become infinite. Expansion of the natural logarithm function leads to the well known result that the maximum value of C is P/KT, the so-called "infinite bandwidth" channel capacity.

mission to approximately 2.0 MHz. Transmit as FM with no pre-emphasis using ± 9 MHz peak carrier deviations. Demodulate using feedback techniques. This will yield minimum acceptable video given a P/KT of +80.0 db-Hz. This is the minimum performance threshold used in Figures 4 through 13.

Range and Range-rate Tracking. - Three general types of active systems of interest are identified in Table A-1 as either INR, CNR, or CR. In each, range-rate data is of primary interest. Such data should not be limited by additive system thermal noise but rather by instrumental uncertainties. Table A-2 gives estimates of P/KT requirements for both TDRS/user and user/TDRS based on a more complete treatment available in the GSFC TDRS study.

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13. Work performed under Contract NAS5-11608.

TABLE A - I

Classification of Tracking Schemes for TDRS Applications

Turnaround Transponder Type			Method of Range Measurement	Method of Range-Rate Measurement
Designation	Description	Example		
Incoherent nonregenerative (INR)	Modulates received signal on local carrier	GRARR crystal transponder	Two-way propagation time of harmonically related sine wave subcarriers	One-way carrier Doppler
Coherent nonregenerative (CNR)	Synchronous demodulation and remodulation on phase-coherent carrier	USB, SGLS, and JPL transponders	Two-way PN code	Two-way carrier Doppler
		GRARR phase-locked transponder	Two-way sine wave subcarriers	
Coherent regenerative (CR)	Synchronous detection, correction, and modulation on phase-coherent virtual carrier	See description of proposed system in Reference 7	Two-way PN code	Two-way Doppler on virtual carrier

TABLE A-2

P/KT Requirements for Mk 1 Tracking Systems

Tracking Scheme and Frequency	Minimum P/KT Requirement		Discussion of Rationale
	TDRS/User Link (db-Hz)	User/TDRS Link (db-Hz)	
GRARR INR VHF, 20-kHz range- tone capability	+50	+50	Maintain 0 db P/KTB in noise bandwidth of GRARR transponder; overall system P/KT in ground receiver sufficient to be below the "knee" of thermal noise sensitivity curves of existing GRARR equipments.
CR VHF (hypo- thetical Mk 1 tracking system)	+40	+40	Noise sensitivity threshold of existing VHF range-rate equipments (GRARR).
GRARR INR S- band, 100 1-kHz range-tone capability	+57.4	+50	Same rationale as used in the case of the GRARR INR VHF system.
SGLS/USB CNR S-band	+40	+40	Noise sensitivity threshold of SGLS & GRARR S-Band range-rate systems.

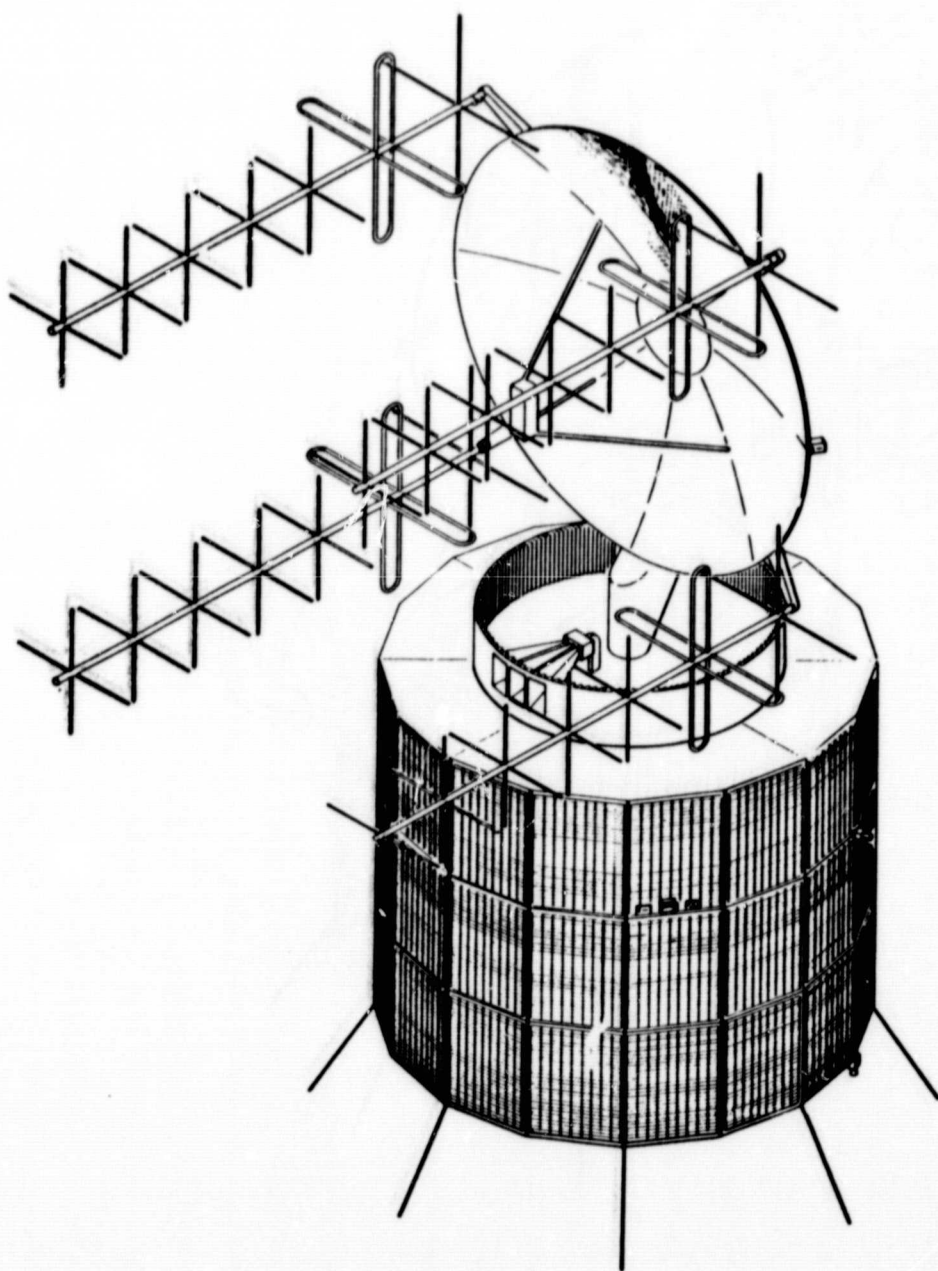


Figure 1. The GSFC Mark 1A TDRS Spacecraft Concept.

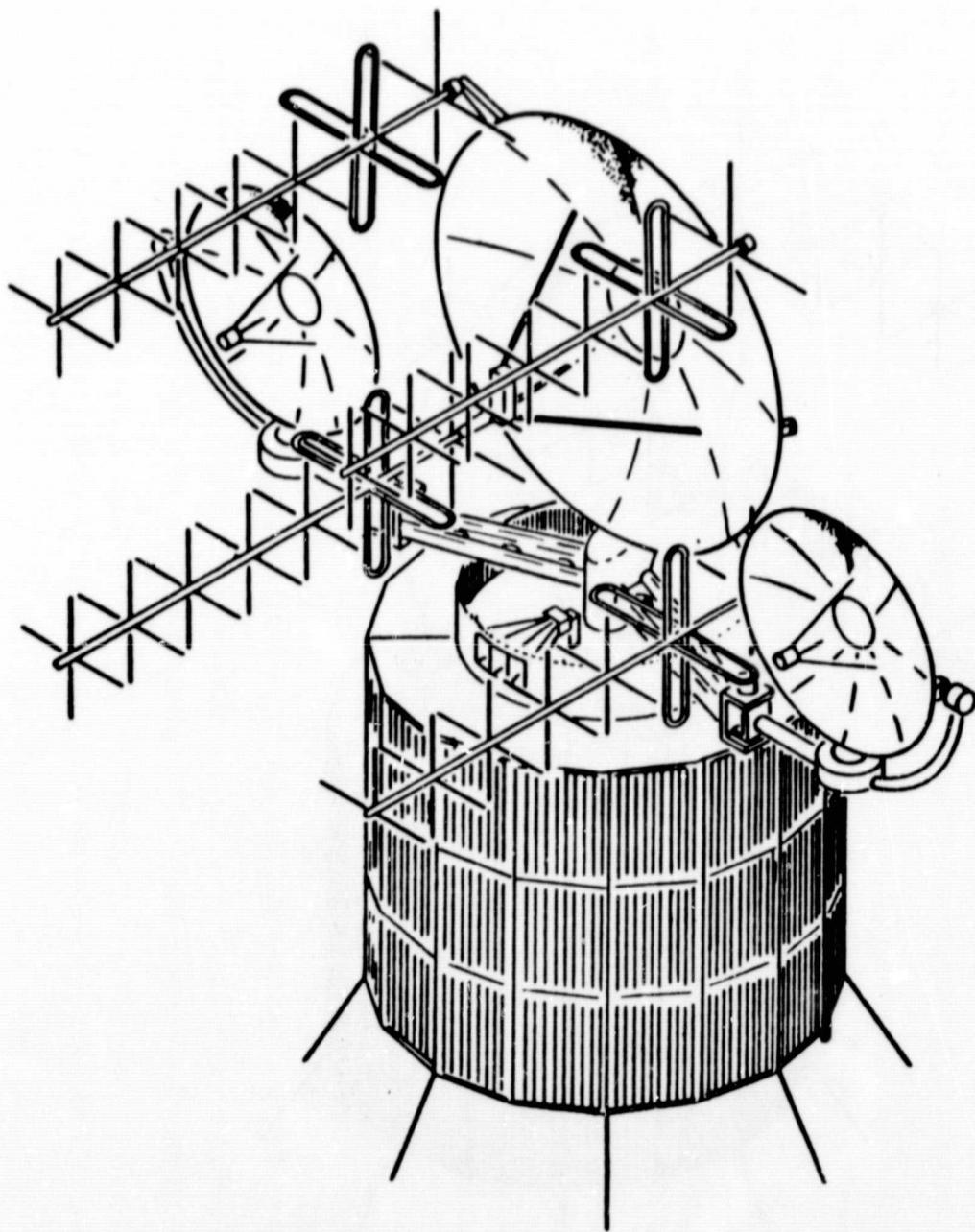


Figure 2. The GSFC Mark 1C TDRS Spacecraft Concept.

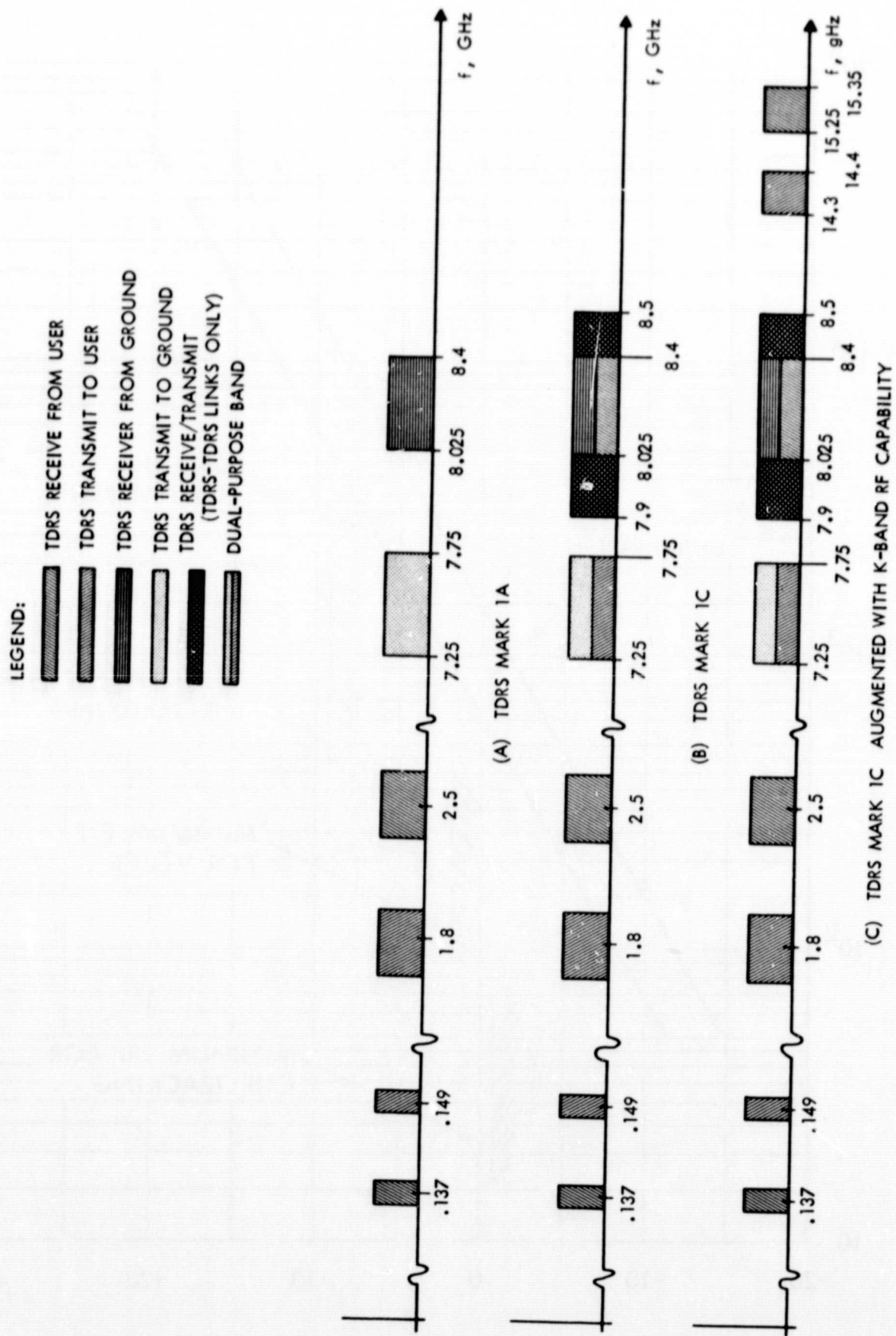


Figure 3. Working frequency plans for the GSFC Mark 1 TDRS system.

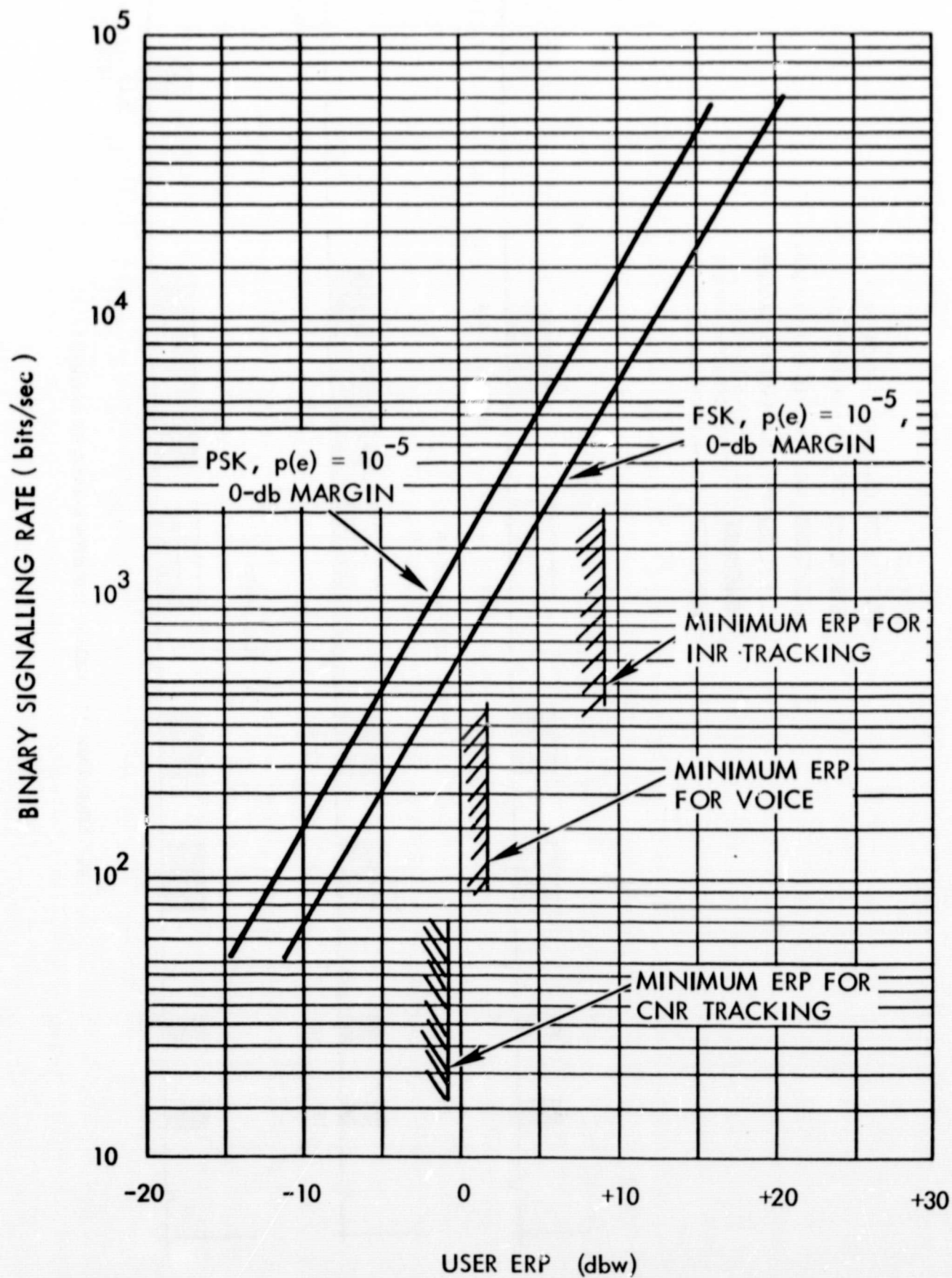


Figure 4. Signaling-Rate Relationships for User/TDRS VHF Link

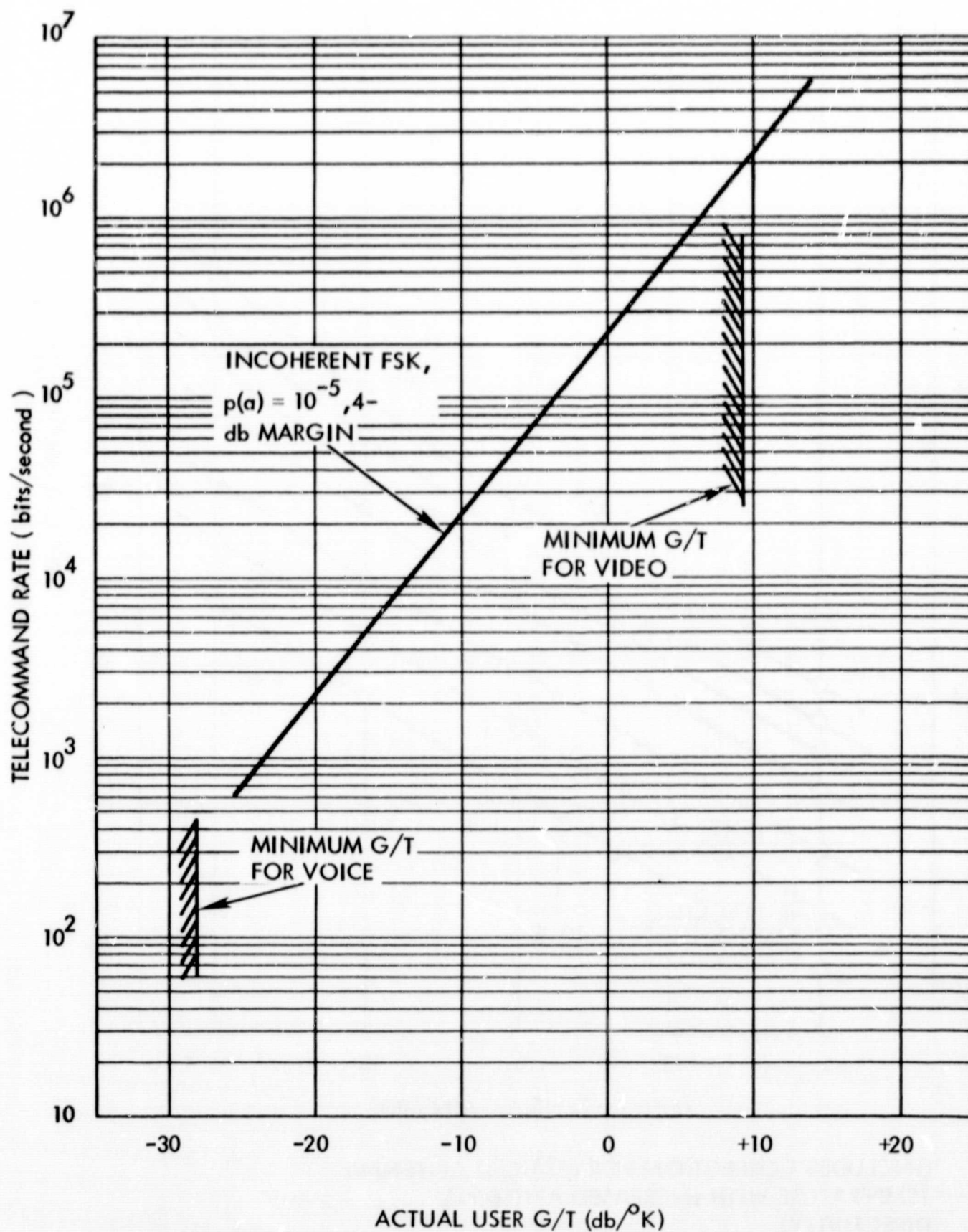
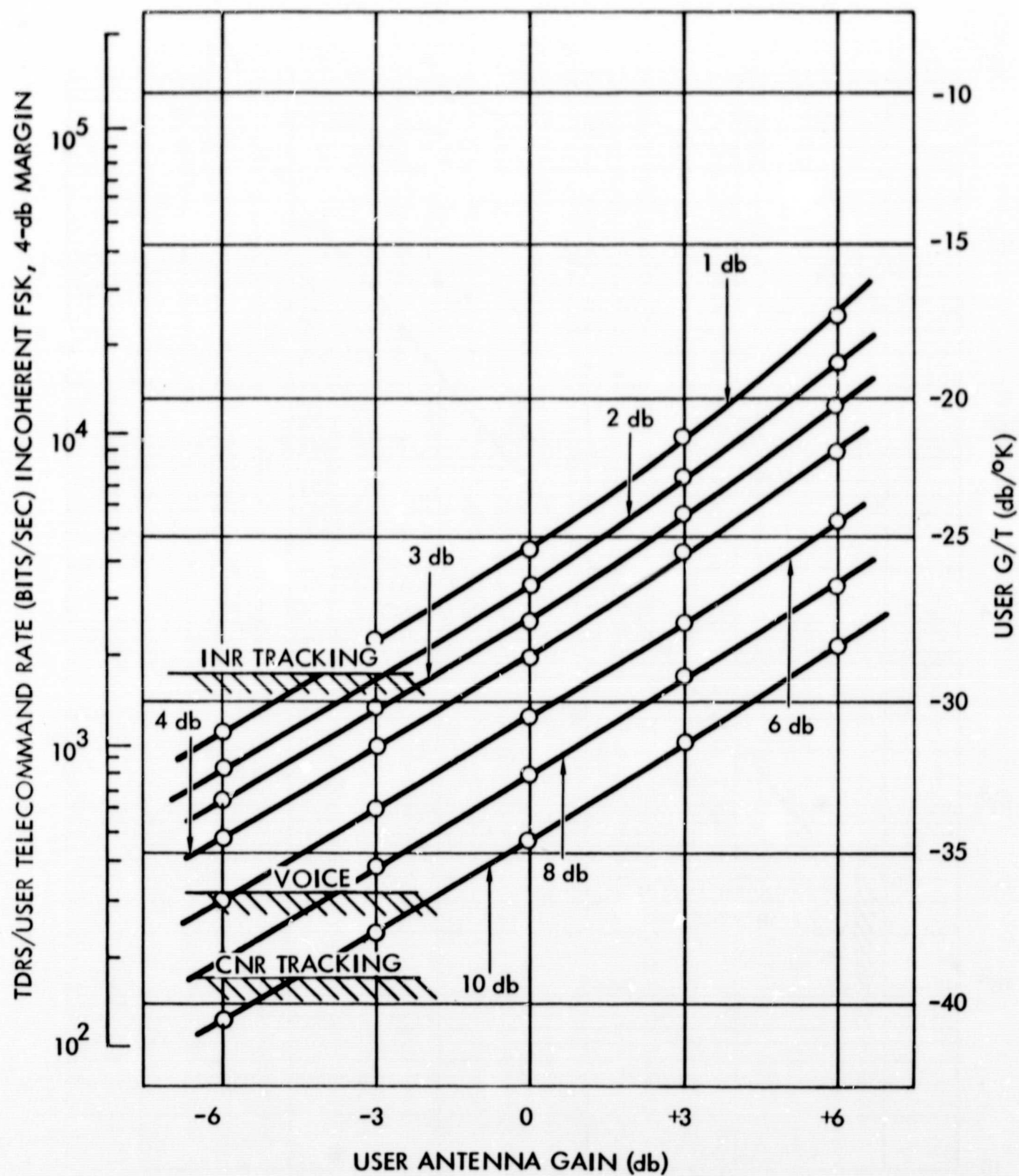


Figure 5. Signaling-Rate Relationships for TDRS/User X-Band Link
 (Version C TDRS Using an 8-ft Parabolic Antenna)



(INCLUDES CORRECTION FOR REDUCED ANTENNA TEMPERATURE WITH INCREASED ANTENNA DIRECTIVITY)

Figure 6. VHF User G/T and Signaling Rates vs Antenna Gain (Noise Figure in dB as a Parameter)

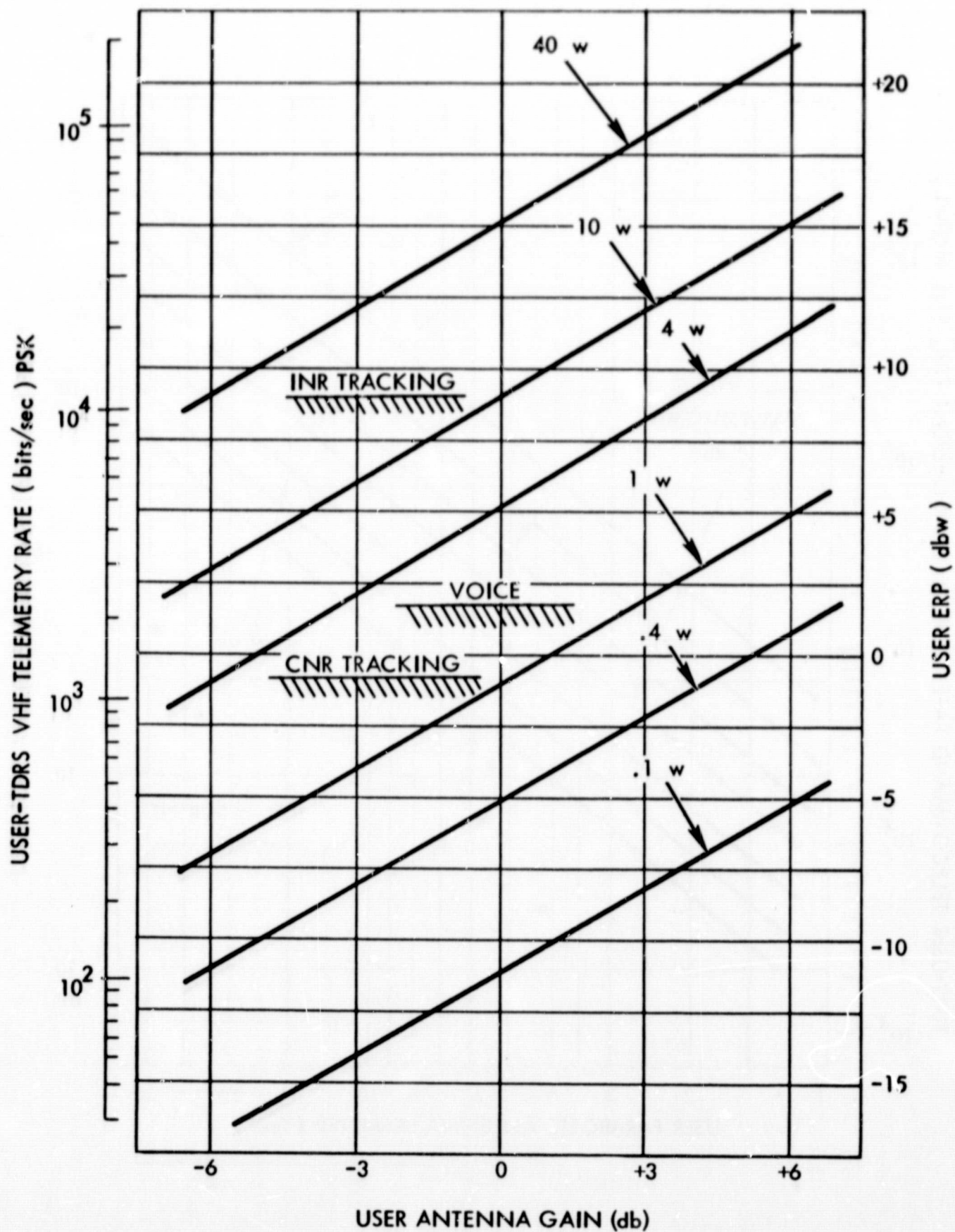


Figure 7. VHF User ERP and Signaling Rates vs Antenna Gain (Transmit Power as a Parameter)

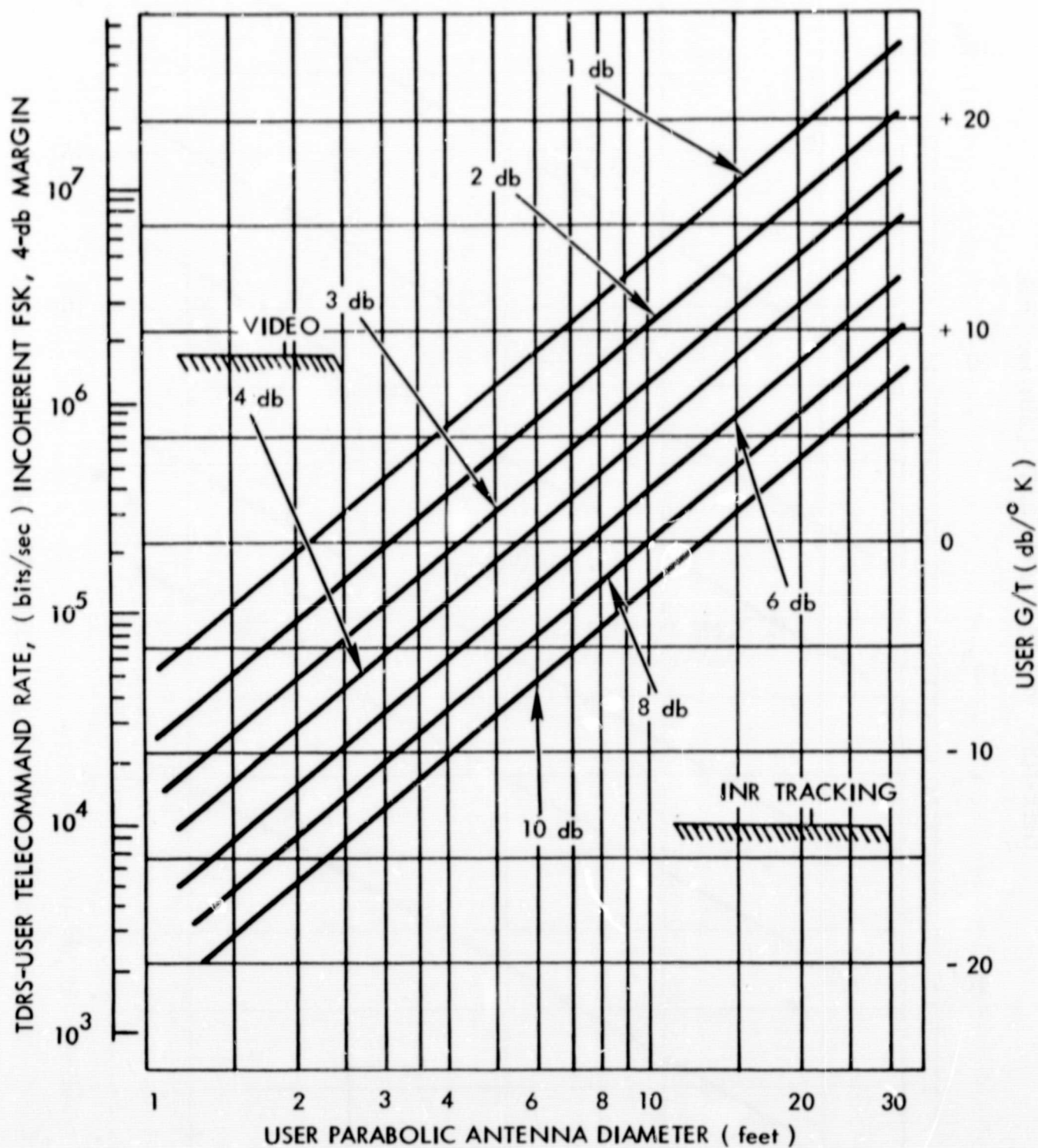


Figure 8. S-Band User G/T and Signaling Rates vs Antenna Diameter (Overall Receiver-Noise Figure in db as a Parameter)

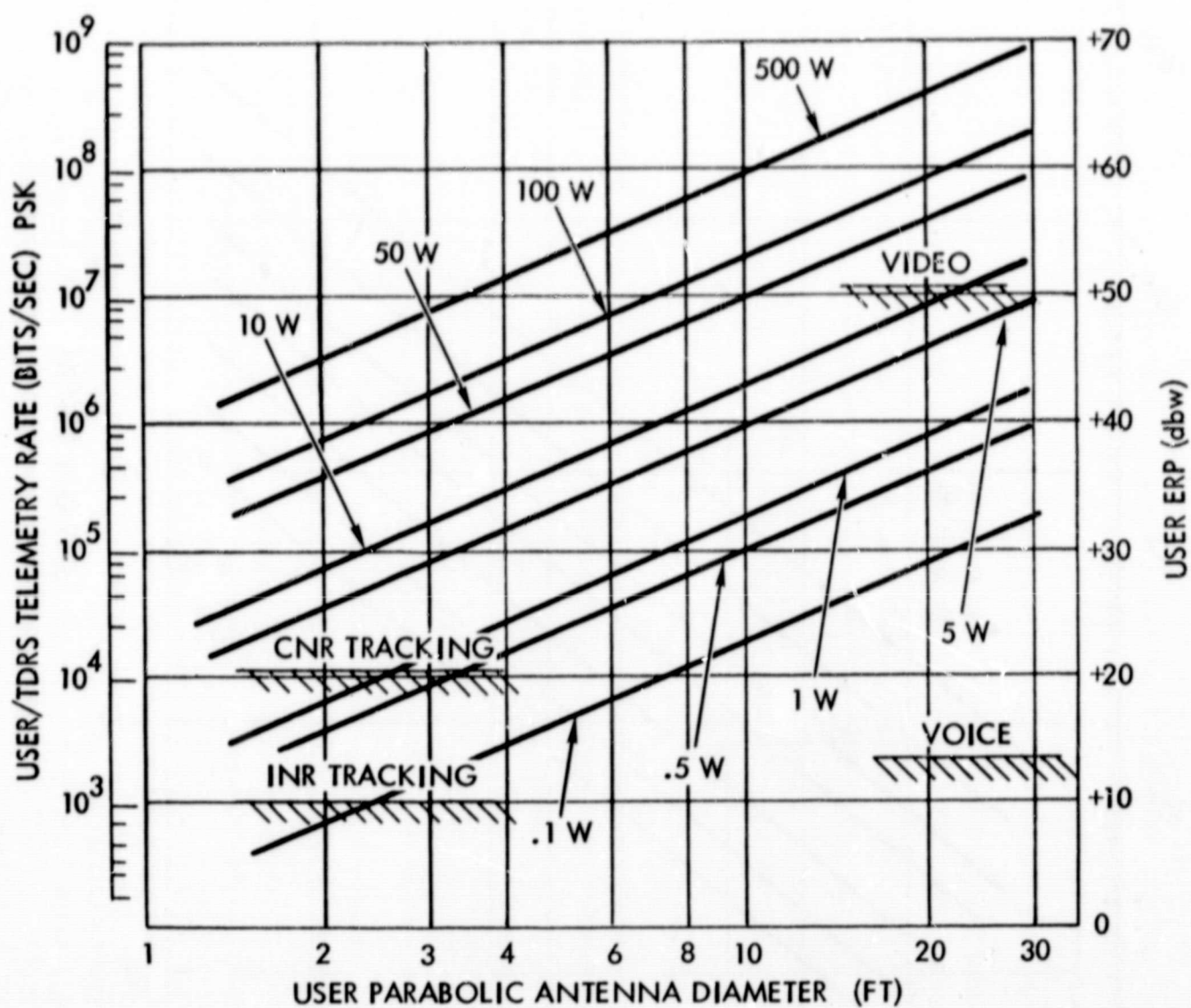
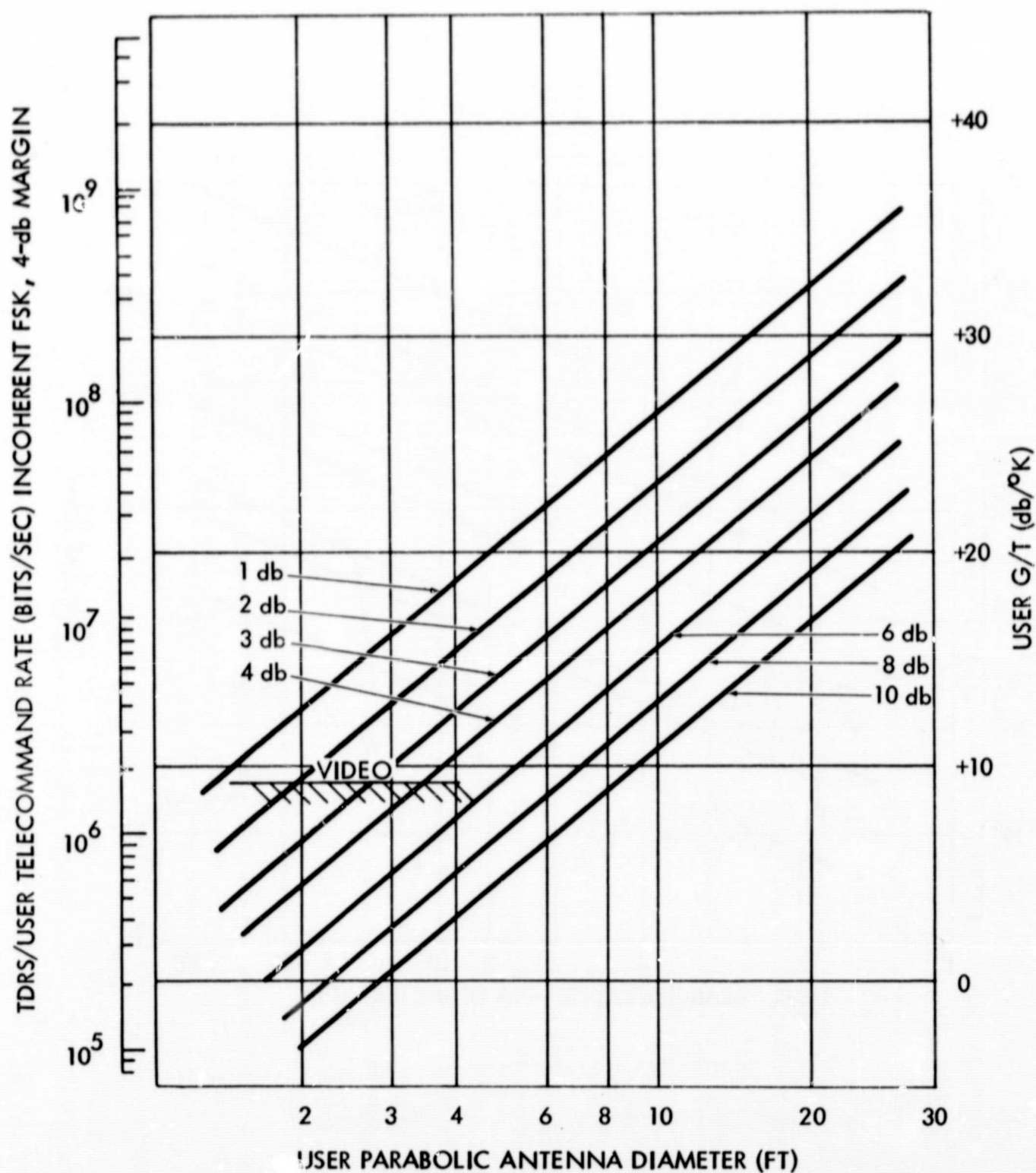
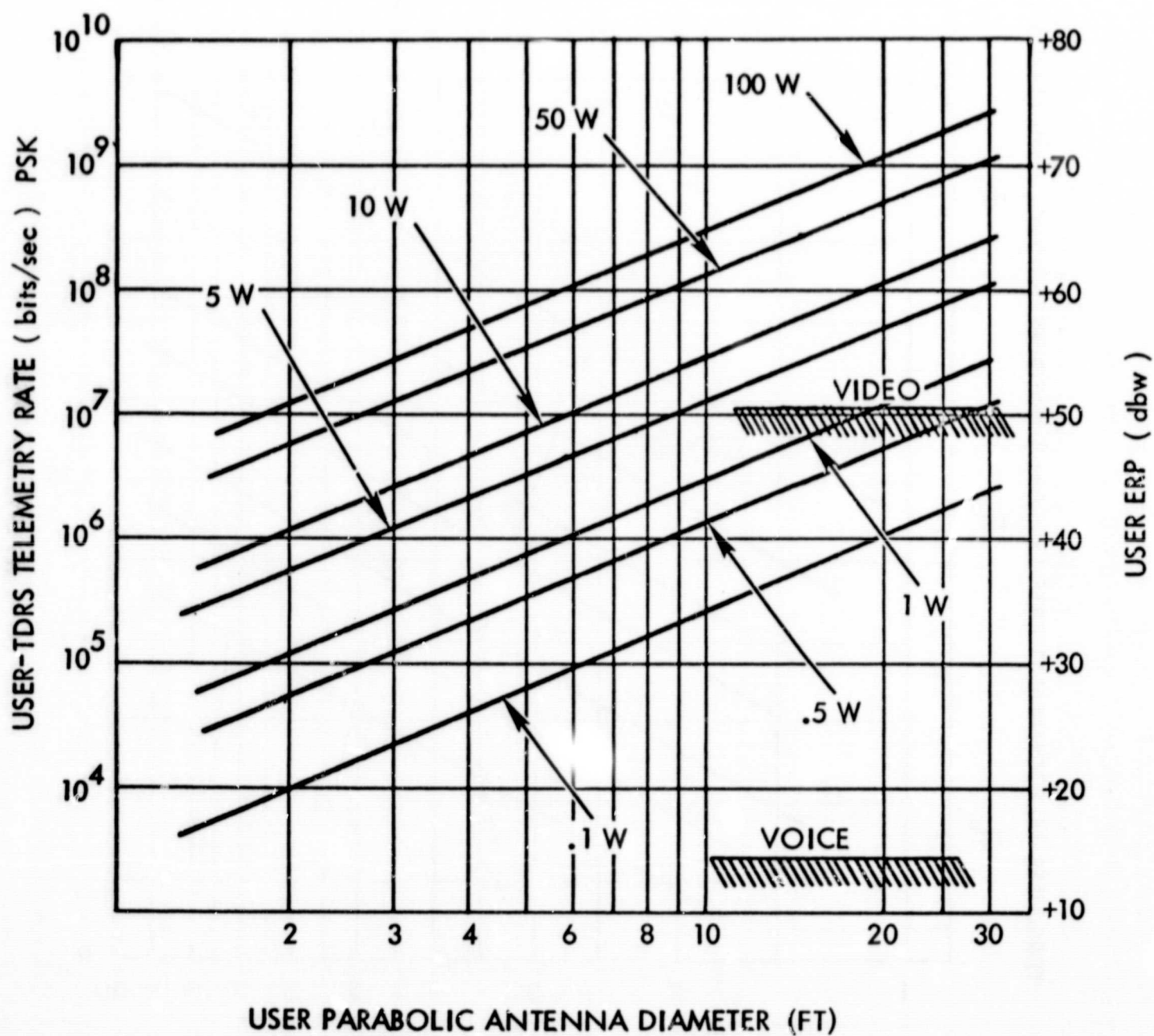


Figure 9 . S-Band User ERP and Signaling Rates vs Antenna Diameter
(Transmit Power in Watts as a Parameter)



VERSION C TDRS TRANSMITTING USING 8-FT DISH

Figure 10. X-Band User G/T and Signaling Rates vs Antenna Diameter (Overall Receiver-Noise Figure as a Parameter)



(VERSION C RECEIVING USING 8-FT DISH)

Figure 11. X-Band User ERP and Signaling Rates vs Antenna Diameter
(Transmit Power as a Parameter)

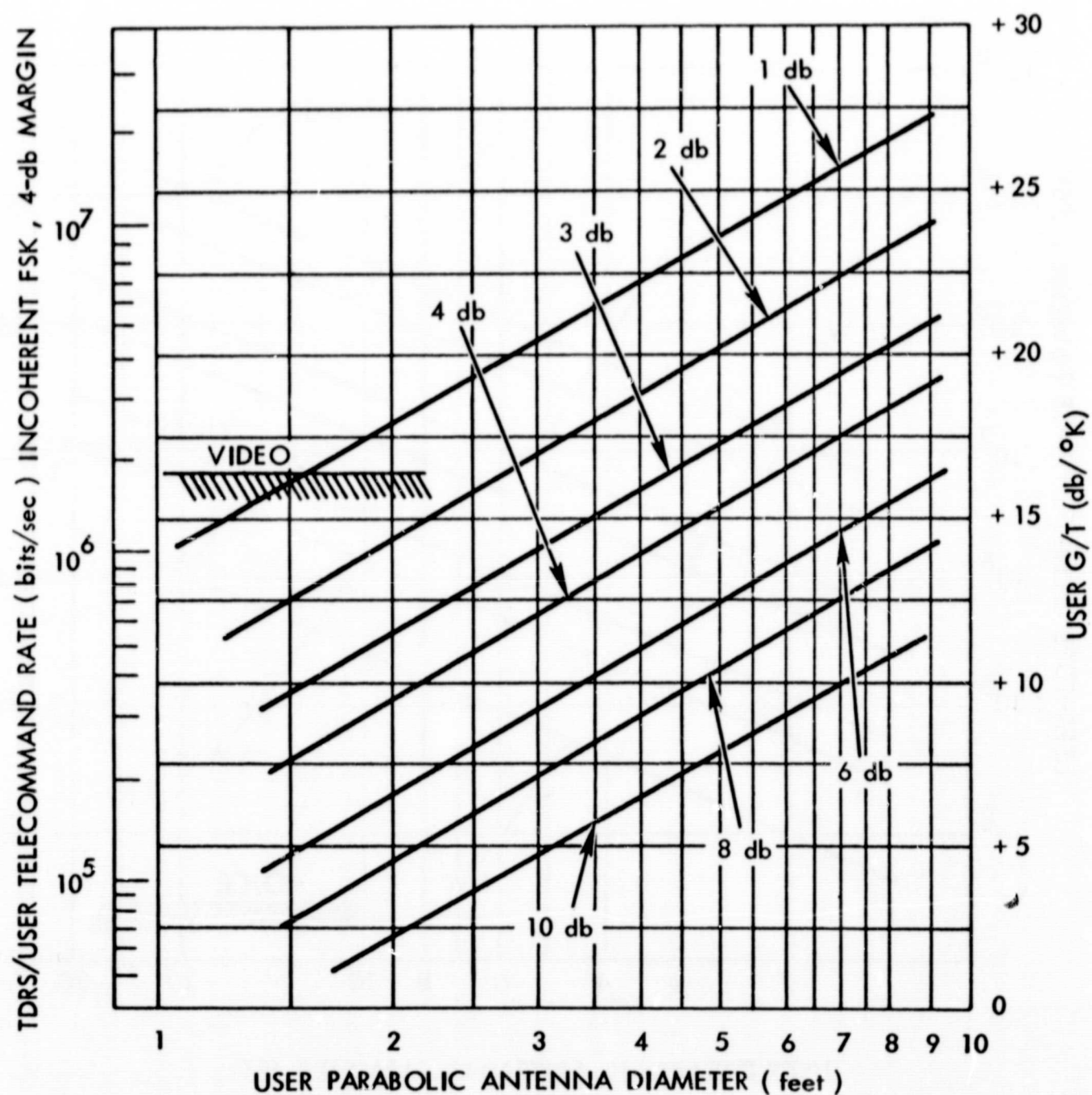


Figure 12. K-Band User G/T and Signaling Rates vs Antenna Diameter (Overall Receiver-Noise Figure as a Parameter)

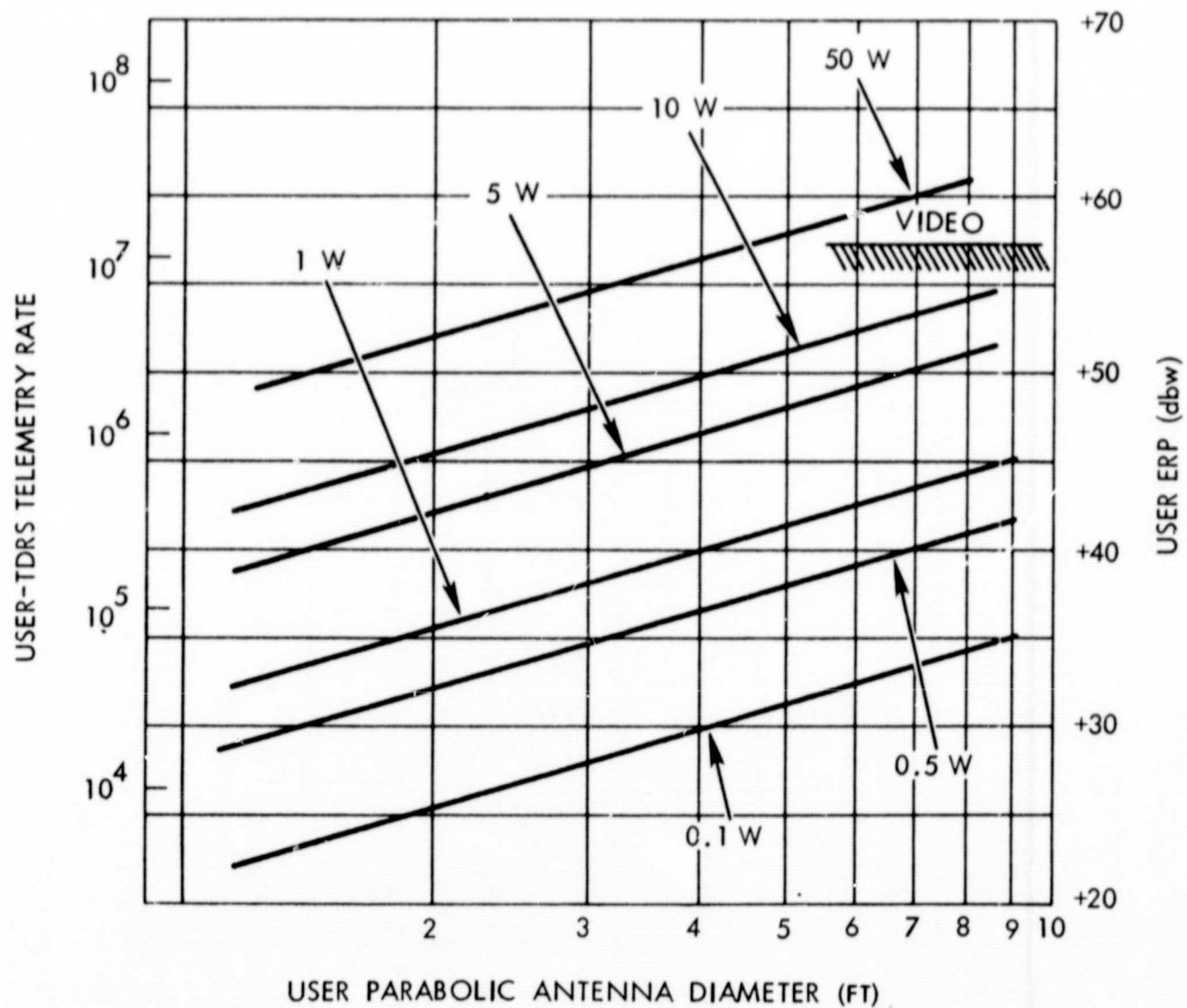


Figure 13. K-Band User ERP and Signaling Rates vs Antenna Diameter (Receiver-Noise Figure in db as a Parameter)